

**Establishing
Engineering Methods and Criteria
Required by Predictive Analyses for
Mechanical Reliability
of MEMS Structures.**

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Introduction

The expanding areas of MEMS applications are often characterized by demanding operating conditions or harsh environments for those sensitive devices. Although packaging represents a solution to some of the hazardous parameters - an issue that has not been totally resolved yet - there are other factors that need to be assessed.

MEMS applications under development today encompass the fields of automotive, spacecraft components in the form of sensors and actuators, military applications, biomedical applications, etc. Many developing, or already developed, applications involve strong vibrations, especially the demanding space applications where the mechanical behavior, device operational lifetime, temperature sensitivity, radiation tolerance and other reliability aspects must be known precisely. The operation of those materials is critical for the success of the mission since the devices are typically incorporated in vital parts of the spacecraft navigational systems, acceleration control or temperature measurement systems (vibratory rate gyroscopes, angular, linear and resonant accelerometers, gas chemistry analyzers, etc.). A future spacecraft will include micro-inertial measurement sensors, micropropulsion systems, microgyroscopes, etc. Those microdevices will be exposed to large forces during launch and reentry conditions that can result in accelerations a thousand times gravity. Intense radiation will be another factor whose effect on the mechanical behavior and device life time under space conditions is not known. Today's applications cover also the fields of advanced military equipment, missile arming, as well as detonation and missile safety systems.

Other applications such as micropumps and microvalves involve liquids whose properties and the way they interact with the structural material are not known. Humidity can be destructive for moving parts of MEMS, since operation (post release) stiction phenomena can be disastrous for the microsystem's operation. Chemical environments including acidic solutions and aggressive chemical agents demand the use of better materials other than polysilicon which is virtually the only material that has been tested until now. However the entire effort failed to establish general criteria that will be used in the future as standards to assess new material performances.

The major effort in the MEMS field so far has been dedicated to the process and method development and the evaluation of the field potential. However the mechanical study and evaluation of micromachines will provide the guarantee for the viability of all future advanced structures. Understanding their behavior is important for the further development of more complicated and multi-functional microsystems.

I. The Role of Mechanics in Reliability Assessment

The assessment of whether a manufactured part will ultimately serve properly (reliably) in an identified environment is the essential and challenging goal of the (structural) engineer. This principle holds for macroscopic structures as well as for small devices.

It is necessary to discuss the building blocks of a structural analysis which is the basis of a reliability or risk evaluation. First we define mechanical “failure” of a device as unsatisfactory functioning under an anticipated design load environment. The “mode of failure” may be in the form of device fracture, excessive deformation of a device component (such as could lead to electrical short circuiting) and/or combinations of the two arising from the growth of a fatigue crack(s) which constitutes progressive fracture accompanied by increased component compliance.

The proclivity of mechanical failure is typically assessed by **Solid Mechanics Methods** that are based on the **Principles of Physics**. This is achieved today routinely for very complex structures and with a potentially high degree of detail through finite element (FE) computations. The proper application of the FE method depends, however, totally on the validity of the physical material parameters that enter the analysis: It provides a quantitative set of information against which risk judgements can be made. If statistical variations of the parameters governing the geometry, material parameters and load prescriptions are available, the solid mechanics analysis provides a statistical or probabilistic distribution of failure occurrences.

The input into the Solid Mechanics Analysis comes from three building blocks, namely

- ✓ **Geometry** of the structure
- ✓ **Material properties** of the components of the structure, and
- ✓ **Loads** acting on the structure, including those due to **residual stresses**.

The output from the Solid Mechanics Analysis is a set of “required” deformations and/or stress components $\{\mathbf{R}\}$, which are then compared for the risk analysis against “allowable” values of material or design parameters $\{\mathbf{A}\}$, such that the difference $\{\mathbf{A}\}-\{\mathbf{R}\}$ (>0) becomes a quantitative indicator of how closely the structure approaches failure for the loads considered.

For macroscopic structures this is a well-understood practice, which also allows for factoring in a certain degree of lack of knowledge on certain aspects of the overall problems. For MEMS-sized structures this process is equally simple, **provided** the physical properties and the detailed geometry are known. That is where today the major difficulties arise. This is true with respect to the uncertainties that derive from the manufacturing process, and, in particular, how the solid mechanics parameters for the MEMS structures are affected by processing variables.

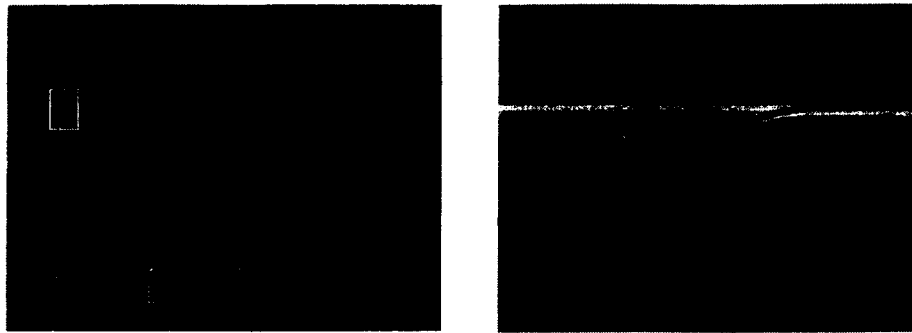


Figure 1: Fractures caused by launch environment

Material Properties: Because current MEMS structures tend to fail in a brittle manner it is believed that the material can be represented by linearly elastic, though probably anisotropic, constitutive descriptions up to the point of fracture/failure. Thus Young's moduli and Poisson's ratios need to be available. Because the failure initiation arises in a domain measured in nanometers, the use of macroscopically determined properties is highly questionable. In addition to these deformation properties, for fracture analysis purposes the ultimate properties (allowable) need to be determined in the form of maximum stress and/or fracture energy. Of course, fracture energies need to be determined differently depending on whether they are associated with delamination (separation) of one layer from another, or whether fracture occurs within one layer only.

Geometry of structures: This topic includes the obvious dimensional layout of the MEMS structure, which most often, though not always, is a nearly two-dimensional structure with the third dimension being very small compared to the planar ones. Besides the over-all dimensions the details of corners and notches are important because they act as stress raisers. Today many designs incorporate very sharp corners (say 90°) which figure heavily in the failure/fracture initiation (see figure 1). Similarly, grain size, etch holes and surface roughness become important structural defects at this size scale. For example, production variations occur in roughness in two ways: (1) The amplitude changes with etch time, and (2) the shape of the depressions [see section 2 below] provides for (variable) geometries that cause stress raises, even though the overall roughness may constitute only about 5% of the thickness.

Load specifications: These derive from the expected use conditions, and may be specified as a most severe condition, or if known in a statistical distribution sense. For ease of discussion, especially in a space related environment, one may consider these loads to derive from

1. static conditions such as residual stress along with additional steady state loads (gravity),
2. high acceleration launch loads, and
3. vibration loads.

These loads may act individually, but are more likely to operate in combination under general launch applications.

Solid Mechanics Analysis: Making use of this information the solid mechanics analysis (usually referred to as deformation and stress analysis) provides detailed stress and strain information at practically every point in the structure, including energy changes associated with the growth of cracks that lead to device failure.

The above classification can be also viewed by the designer's manufacturer's point of view where the same factors can be classified into:

- **Properties that depend on the choice of material:**
 - Elastic parameters (basic parameters to determine the behavior of the structures)
 - Fracture parameters. Fracture mechanics is a developing field but has reached the necessary maturity to be employed in the field of micromechanics of MEMS. This approach illustrates the failure behavior of structures and represents the modern approach in mechanics of structures.
 - Fatigue and long term operation effects on structure integrity.
- **Other parameters that result from the distinct character of the process:**
 - Residual stresses
 - Surface roughness
 - Grain size
 - Stiction phenomena.
- **Parameters that result from geometrical features and design of the specimens:**
 - Sharp corners
 - Notch sensitivity, etch holes effect on fracture
 - Sandwich structures that result by multiple structural layers raising bonding/debonding issues.

II. Review of Current Practices and their Limitations

Presently failure tests and analyses of MEMS are based on “Strength of Materials”¹, which assumes material linearity, homogeneity and isotropy, and ignores defects and cracks other than through change in lineal dimensions. This discipline is designed for analyzing smooth beams and plates effectively. Specifically, the discipline of Strength of Materials is not equipped to deal with notches and cracks that are responsible for stress concentrations and fractures. Moreover, there is no room to address the stress concentrations associated with surface roughness that, for MEMS structures, is influenced by processing conditions and responsible for variability in failure initiation. In the few cases when such analyses can be used for crack analysis at the macro-scale, they typically invoke the concept of “small scale yielding” which allows ignoring nonlinear material behavior in a “small region”² around the tip of a crack. In the present context the whole structure could fit into such a “small scale yield region”. Moreover, the elastic properties of structures vary as a function of size once the scale is in the micron and sub-micron range, so that the assumption of homogeneity is no longer valid: Strength of materials concepts is thus, at best, questionable. It is for this reason that fracture mechanics based on elasticity theory (and plasticity) needed to be developed for structural failure analyses.

Thus, if one is interested in the fracture of a beam measured in terms of meter dimensions, the fracture process is actually governed by a region a thousand times smaller, namely the region around the tip of a crack. The growth of such a crack cannot be described simply in terms of the total load acting on the beam: Elasticity (and plasticity) theory provide the connection from the macro load to the small and failing region at the crack tip. In the absence of a pre-existing macroscopic crack, its initiation and evolution from an apparent continuum is described in terms of similarly small domains. It is the purpose of proposed research to provide the experimental tools and concomitant analyses for fracture mechanics purposes at the micron scale for MEMS reliability determinations.

Macroscopic fracture studies are supported by a host of experimental methods developed over many decades in parallel to the needs for analyses. For example, strain measuring devices (strain gages) are so commonplace that today (macroscopic) structural evaluation is unthinkable without them. Even though such strain gages are small by standard engineering notions, they are huge compared to the total size of the typical MEMS. In addition, more refined, mostly optics-based methods [photoelasticity; moiré, moiré-interferometry; Twyman-Green interferometry, deformation gradient sensing, shearography, for example], exist for deformation (strain) determination that form the foundation of our analyses of structural reliability in a research, development or applications environment.

¹ This is really a misnomer, since the analysis method does not really refer to a material breaking strength as understood today, but merely addresses the stiffness of structures, or their resistance to deformation under loads.

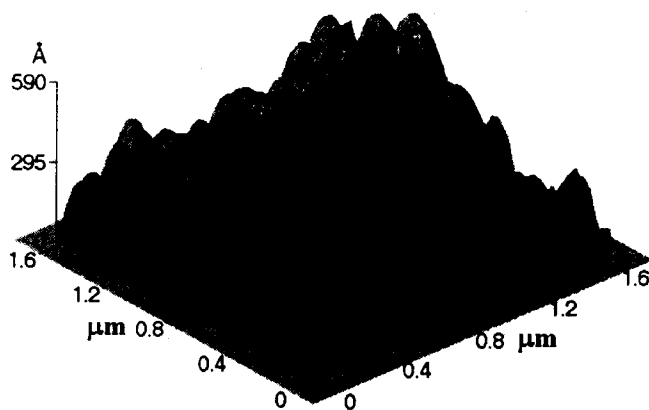


Figure 2: Three-dimensional rendering of the surface topography of a $1.6\ \mu\text{m} \times 1.6\ \mu\text{m}$ region revealing the columnar structure of the material and the surface non-uniformity. The z-direction is exaggerated compared to the lateral dimensions to make the grain structure more apparent. The image was obtained using an AFM in the Contact Mode.

Upon considering the corresponding situation with respect to the micro-device field one notes that the whole structure has dimensions larger than or comparable to the failure domain for macroscopic structures. Any direct scaling from the macro to this micro scale is, at best, highly questionable. To the limited extent that fracture studies exist for cracks in the tens to hundreds of microns in length, marked deviations from typical, macroscopic fracture mechanics behavior have been noted³ which are measured by factors of two or more! For MEMS devices the cracks are typically still smaller and **no publication or reference to work on fracture in this size scale could be found yet**, nor are we aware through personal contacts within the MEMS community that investigations at the size scale discussed are in progress, other than attempts to manufacture cracked MEMS. Some of the currently used practices are summarized below and in the attached review paper in the appendix.

Deformation field measurements at the macroscale are an essential ingredient of fracture analysis and theory verification. Commensurate measurement tools and data processing methods for the micron and sub-micron scale do not yet exist; any future study must address this urgent need. The fact that the technology of probe-microscopy is well accepted and microscopes of this type are much more affordable than SEMs and TEMs makes this technology for small scale fracture and failure mechanics measurement methods highly attractive for many laboratories. It is the intention to estimate also to what extent the method devised here for probe microscopy can be transferred to SEM and TEM investigations, so that many laboratories may acquire capability in sub-micron strain field analysis.

² Tens to hundreds of microns for "brittle" materials and millimeters/inches for ductile solids

³ Freiman, S.W.; White, G.S.; "Intelligent Ceramic Materials: Issue of Brittle Fracture", *J. Intell. Mat. Syst. Struct.*, **6**, Jan 1995.

Current methods available at the requisite small size scales to the investigator of mechanical behavior are limited. They are grouped into methods governed by (a) Strength-of-Materials methods; (b) Scanning electron Microscopy; (c) Transmission electron Microscopy.

“**Strength-of-Materials**” evaluations deal with property deductions from a whole structure, rather than from a subdomain. One method favored today is based on the dynamic response of

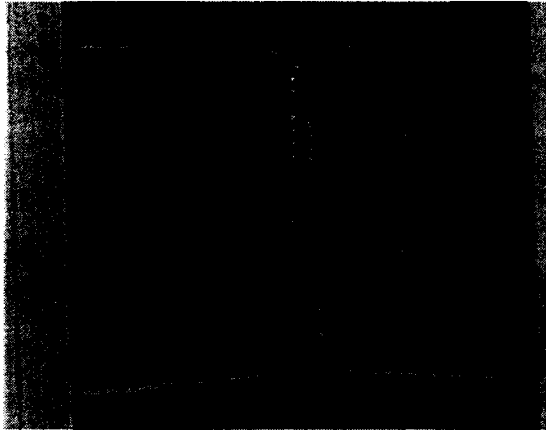


Figure 3: Vernier arrangement for measuring displacements

vibration excited cantilever or plate shaped components. With micron sized components the measurements yield only average properties at that size scale and will not address property or deformation gradients that exist in such small devices when fracture/fatigue prevail, even if notches and special plan section are employed. Fracture evolution is (ostensibly) monitored through change in the natural frequency. There is definitely a lower size limit to which this method will speak, because it ignores the variation in mechanical properties throughout the structure (properties inhomogenities) as the latter decreases in size into the micron range. An alternate method uses the **pressurization of membranes** which, again, addresses only the average properties at the super-micron size scale, since they are typically on the order of a millimeter in extent, though one to two microns thick. While multiple properties such as modulus and Poisson’s ratio are accessible in principle⁴, the method is not very accurate since the requisite precision in dimension determination naturally and easily induces errors on the order of 30% (problem of metrology). The most often cited method for deformation measurements employs verniers (*c.f.* Figure 3) which is a very crude device in comparison with what probe microscopy can achieve as described below.

Scanning Electron Microscope: Whenever small dimension arises the **SEM** is the favorite tool to resolve dimensions. The SEM is today the primary tool for studying MEMS behavior: It is used for determining dimensions and to monitor displacements —through verniers (*c.f.* Figure 3) constructed onto a MEMS device. Attempts at extracting strain data have not been very successful, and the need to construct in-cavity deformation equipment is a serious drawback. SEMs share problems of deformation studies with the

Transmission Electron Microscope: In addition to the need to operate also in a vacuum the TEM has the disadvantage that it can only provide average transmission images and thus

⁴ Breton, F., Knauss, W.G. “Error Limitations in the Determination of Mechanical Properties of Thin Films”, *J. of Reinforced Plastics and Composites*, Aug. 1996.

averages all properties through the thickness of any structure; it is thus not applicable to bending type deformations, and, moreover, provides only a two dimensional image, whereas the new method proposed here can ultimately provide three-dimensional displacement components of a deforming surface.

Perhaps the most limiting feature of all these methods is, with the possible exception of the Bragg angle scattering method, that average properties are measured. Because of the very high spatial resolution capability (nanometers) of the proposed method the latter has the potential to yield considerable higher detail which is particularly important when one deals with inhomogeneous deformations such as associated with fracture.

The drawbacks of the currently used practices can be summarized in the following:

- There is no evaluation of how the manufacturing process affects the end product. The reported works are independent, tailored to specific fabs with no comparison with others or manufacturing methods. Most attention is dedicated to the manufacturing processes and methods, number of layers and materials used. There is no evaluation of an optimum process regarding structures with optimum integrity and mechanical properties.
- The work that has been conducted so far does not address the local properties but rather global measurement efforts carried out which completely overlook the local nature of failure and behavior of those devices in the micro scale.
- There is no consideration given to evaluate particularly “risky” geometries and the geometrical features of the specimen surface and their effect on the operation of the overall structure.
- There is presently no general approach to allow for testing of new materials which are becoming increasingly more necessary for special applications that involve high temperatures or demand high fracture strength and modulus of elasticity.
- Commercial packages use mechanical properties borrowed either from bulk properties tables or arbitrarily from literature papers often not being applicable to the specific material that are used to simulate.

There is an obvious need for a coordinated effort to focus all these independent practices into a methodology that will become the standard in MEMS testing and evaluation and that is the target addressed in white paper.

III. An Integrated Reliability Analysis Program

One (impractical) avenue of accumulating reliability information on specific structures is to test large numbers of devices over a range of conditions derived from, say, launch environments. If enough devices are tested, this approach provides statistical data for risk evaluation. Of course, the data acquisition must include sufficient variation in the production variables to assure complete coverage of the statistical parameters that affect the ultimate performance of a device.

From a practical viewpoint this is much too expensive a proposition to be exercised for standard operations. Instead it is prudent to use the same type of structural analysis methodology employed in large scale structures. However, the tools for doing this are not uniformly available, and it is the goal of the anticipated research and development to provide the requisite tools.

Finite element evaluations could be carried out today, if the right physical properties were available. Thus, in principle, the problem is simple: Measure the requisite properties and the residual stresses in the devices. Real life looks different:

Because properties and (micro)geometries are subject to manufacturing variations there is as yet no guarantee that the “right” properties would be measured for a particular fab. Moreover, to the extent that residual stresses vary also from lot to lot, it is necessary to establish these parameters - or at least a sufficient number of indicators- for each wafer or fab.

To this end each wafer needs to incorporate one or more **test structures**, on which specialized characterization tests are performed routinely to characterize the particular fab as well defined input into the solid mechanics analysis that then produces the **reliability estimate**. It is anticipated that ultimately each foundry would have the means and capability to perform these standardized measurements to supply to the customer along with the MEMS hardware.

To establish this frame work for reliability analysis we visualize thus a research and development program that establishes the tools and test methods to accomplish failure and reliability analyses for MEMS structures that are commensurate to those available and utilized currently for macro structures. This is done with the need in mind to establish the variations derived from manufacturing variables at a size level that is not approached for that purposes today. Details of what the major components of that development effort are given in the subsequent discussion. In order to better convey the interaction of the various component of the overall plan, we present in figure 5 a global “flow diagram” of the interdisciplinary topics. The areas requiring virtually all of the research and development are identified by the domains marked in gray.

In the sequel we describe in more detail the essential tools and/or methodologies required to implement any technically meaningful reliability analysis process.

As mentioned before, the emphasis in MEMS evolution is mostly on **developing manufacturing methods**. A literature survey will quickly produce volumes or hundreds of publications devoted

to how special devices are manufactured and to methods by which that is accomplished. In contrast, one can essentially count on one hand the number of papers that try to cope with the failure proclivity of such devices. By comparison, there is thus **only a minuscule effort devoted to developing methods for mechanical failure prediction**. One reason for this imbalance is that the necessary measurement tools are not in place. It is intended to demonstrate that new measurement capabilities are available and can be developed further to open the macroscopic, theoretical frame work of fracture analysis of the macro scale to the reliability analysis of microstructures. In the past, silicon was the primary structural material, but recent developments point to a diversifying pool of MEMS materials. As a consequence, analysis tools must accommodate a large class of materials.

Any macroscopic machinery, structure or component functions with known reliability only because the requisite analyses are available and have been effectively demonstrated over many years. Such analyses are possible at this time only because of an accurate knowledge of the physical properties of the structure (or its components) for the evaluation of specific failure modes. Today's technology provides ample testimony to the fact that this design and failure evaluation process is "working" very well at the macroscopic scale. The technical backbone of reliability analyses at the macro-scale is the knowledge of what controls fracture, namely cracks, notches and inclusions or other defects, which provide stress raisers of varying degrees.

The principles governing failure behavior have been clarified for a very large range of materials during the last 25 to 50 years. It is clear that the same principles are valid for small structures, however, the material parameters needed for the relevant analyses are scale-dependent when dimensions of microns or smaller are involved (Mesomechanics). Based on historically documented experience it is also clear, that currently used (strength of materials) methods ultimately are insufficient to deal with the reliability problem of MEMS, just as they were inadequate to address them effectively at the macroscopic level. Figure 4 illustrates the temporal evolution of failure analysis for macroscopic structures and the roughly corresponding time line for micro- and nanodevices: Presently (1999) mechanical analyses are typically based on strength of materials concepts, with the need for growth into the fracture mechanics-based reliability issues lying ahead of us.

Currently practiced methods based on strength of materials are inadequate (see discussion below) and this fact makes it necessary to evaluate the structural and fracture parameters of MEMS directly at the micron- and nano-levels. However, in contrast to the relative ease with which we have learned to make such property measurements at the macro-scale the same is not true for these tiny devices.

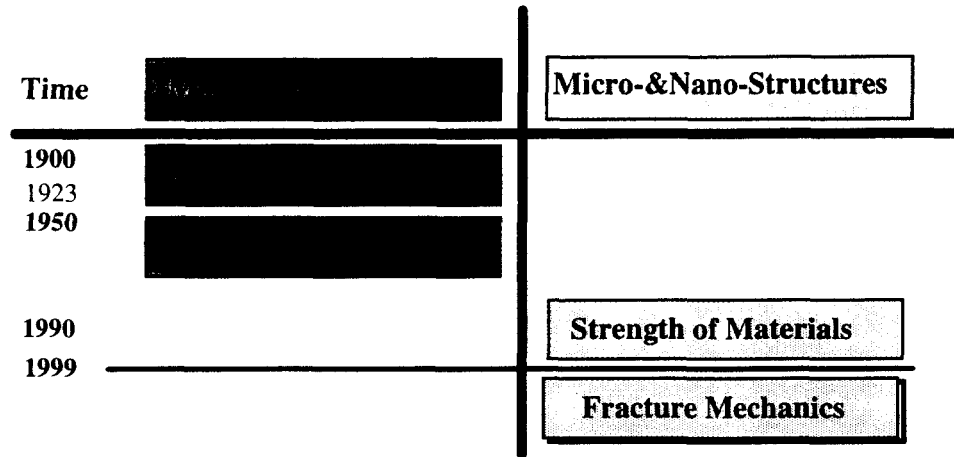


Figure 4: Evolutionary time line of failure prediction methods for macros-structures and for micro-devices relative to the present.

A global approach of the mechanical assessment problem can be synopsized in the following:

- Development of a method (one or more if necessary) to evaluate mechanical parameters using standardized test vehicles. The method will include equipment development, test specimen design and computational methods involvement to form a standard method for testing. Distributed test vehicles on every wafer can serve as measurement spots on the wafer being able to yield local variations of properties.
- Description of the material behavior that results from the manufacture process either by theoretical modeling where available, or, by statistical models depending on the experimental results.
- Extensive study of geometric characteristics which will lead to a categorization of design configurations. Tabulated fracture parameters and effects of geometrical features will form the necessary database for computational codes that will evaluate the integrity of commercially developed MEMS structures. Commercial packages may be replaced by customized special computer codes if necessary.
- This approach will allow for a limited demand of additional tests to evaluate new processes, fabs or individual devices, and provide the capability to predict the properties of new structures based on the available information about the fabrication process and material characteristics and structure design.

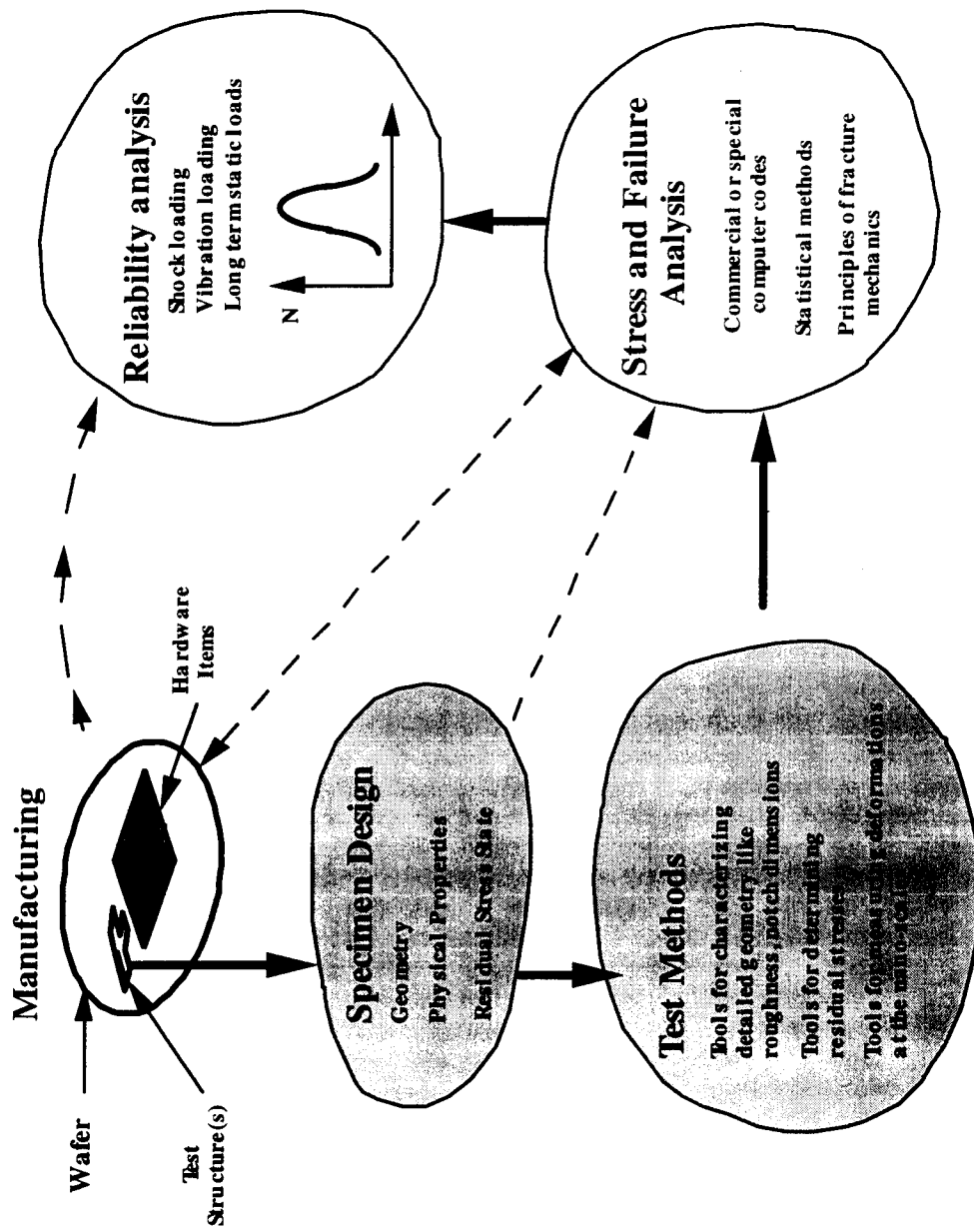


Figure 5. Flow diagram of interacting activities for developing an integrated reliability analysis capability.
Dashed lines represent idealized operations paths

IV. The Future of Mechanics Assessment of MEMS Devices

A. Proposed Method

Two components are needed to implement the proposed work:

- (a) A probe microscope (STM or AFM) and
- (b) digital image correlation capability (code).

The rudiments of both are in place but have not yet been exercised in the context of size scales appropriate for MEMS designs.

(a) **Scanning Tunneling microscope:** Recall that the need for strain measurement requires comparison of a deformed and undeformed body. Typical commercial STMs do not readily accommodate fixtures for straining specimens. Thus a (digital) special tunneling microscope has been constructed in our laboratory that allows placement of a micro-deformation stage under it for recording surface profiles before and after (incremental) deformations. In the meantime, a (commercial) *AFM has been purchased* with the expectation that special loading devices can be constructed for it. Because of the AFM configuration this construction has not been an easy matter but progress is being made to load specimens at increasingly smaller load and size scales in order to deal with MEMS related issues. A photograph of the campus-constructed STM is shown in Figure 6.

(b) **Digital Image Correlation (DIC):** To turn a probe microscope into a strain measuring device requires an ability to convert surface images resulting from sequential loadings into strain and displacement fields. This is accomplished via a digital image correlation algorithm, the current (two-dimensional) version being described here briefly⁵:

A surface profile, as obtained by a Scanning Tunneling Microscope, is a discrete record of the "height" of the surface at grid points assigned to a specimen surface. Let $f(x,y)$ represent the surface profile of a specimen in an undeformed state at point $G(x,y)$, and $g(\tilde{x},\tilde{y})$ the surface profile after deformation at the corresponding point $\tilde{G}(\tilde{x},\tilde{y})$. If the profile pattern before deformation is uniquely related to the profile pattern after deformation, a correlation of these two patterns exists to detect the profile difference that is the object deformation. Let χ be the mapping from the undeformed to the deformed configuration

$$G \rightarrow \tilde{G} = \chi(G) \quad \text{such that} \quad g(\tilde{x},\tilde{y}) = f(x,y) \quad (1)$$

$$\text{or} \quad \tilde{x} = x + u(x,y) \quad (2)$$

⁵ The extension to three-dimensional DIC is given in references by G. Vendroux and W.G. Knauss, "Deform at the Sub-Micron Size Scale: II. Refinements in the Algorithm for Digital Image Correlation", GALCIT SM 94-5, to appear in *Experimental Mechanics*.

$$\tilde{y} = y + v(x, y)$$

with u and v the in-plane displacements of G , and let $\tilde{G}_0(\tilde{x}_0, \tilde{y}_0)$ be the image of $G_0(x_0, y_0)$ through χ ; further, let S be a (sub)set of points around G_0 and \tilde{S} the corresponding (sub)set of point around \tilde{G}_0 .

Assuming that S is sufficiently small, (2) can be expanded into

$$\tilde{x} = x + u(x_0, y_0) + \frac{\partial u}{\partial x} \Big|_{x_0, y_0} (x - x_0) + \frac{\partial u}{\partial y} \Big|_{x_0, y_0} (y - y_0) \quad (3a)$$

$$\tilde{y} = y + v(x_0, y_0) + \frac{\partial v}{\partial x} \Big|_{x_0, y_0} (x - x_0) + \frac{\partial v}{\partial y} \Big|_{x_0, y_0} (y - y_0) \quad (3b)$$

as the linearization χ_l of χ around G_0 . For a discrete set of data define the correlation coefficients

$$C = \frac{\sum_{G_s \in S} [f(G_s) - g(\chi_l(G_s))]^2}{\sum_{G_s \in S} f^2(G_s)} \quad (4a)$$

or

$$C = 1 - \frac{\sum_{G_s \in S} f(G_s)g(\chi_l(G_s))}{[\sum_{G_s \in S} f^2(G_s) \sum_{G_s \in S} g^2(\chi_l(G_s))]^{\frac{1}{2}}} \quad (4b)$$

It is clear that C will be zero when the coefficients of the mapping $\chi_l \{ \dots \}$ are indeed the displacements and their derivatives at G_0 ⁶. The best estimate of these values are determined by minimizing C , which process can be viewed as a non-linear optimization scheme⁷.

⁶ Chu T.C., Ranson W.F., Sutton M.A. and Peters W.H., "Applications of Digital Image Correlation Techniques to Experimental Mechanics", *Experimental Mechanics*, 25(3), pp. 232-244, 1985.

Sutton M.A., Cheng M., Peters W.H., Chao Y.J. and McNeil S.R., "Application of an Optimized Digital Correlation Method to Planar Deformation Analysis", *Image Vision Computing*, 4(3), pp. 143-150, 1986.

⁷ G. Vendroux and W.G. Knauss, "Deformation Measurements at the Sub-Micron Size Scale: I. Design of a Digital Scanning Tunneling Microscope", GALCIT SM 94-4, to appear in *Experimental Mechanics*.

III Deformation Mechanics in a Structural Polymer", GALCIT 94-6, to appear in *Experimental Mechanics*.

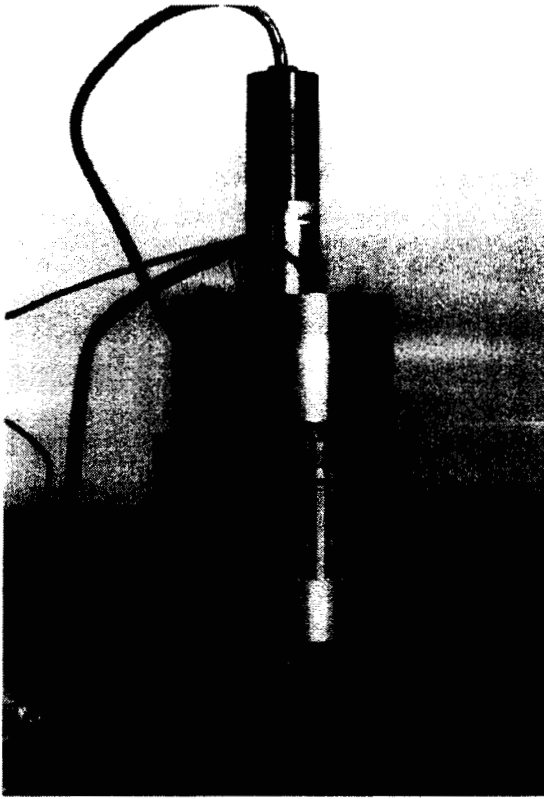


Figure 6: STM especially designed for strain work

The combined scheme of using data acquired with the aid of the STM as input to the DIC algorithm has been tested by translation and uniaxial tensile tests with the following results: The **resolution in displacement field measurements** over a $10 \times 10 \mu m$ area was found to be

- 4.8 nm for the in-plane displacements and
- 1.5 nm for the out-of-plane displacements.

More detail on this development is documented in references 6 and 7.

B. Previous Experience at Caltech

Before proceeding we show an example application of the method to measuring the strain at a yet larger size scale.

A (relatively macroscopic) specimen of (gold-palladium coated) PVC, approximately 0.8 mm thick and 3 mm wide was stretched uniaxially in a straining device which allowed deformation control (via InchWorm) to a precision of about 5 nanometers. The specimen was provided with a (very) small foil strain gage which produced the (solid line) stress-strain response shown in Figure 7. While loading and unloading the specimen, the STM/DIC tool was also used to evaluate the strain over an approximately 16 micron square. While initial measurements encountered some problems with convergence of the DIC code, growing experience yielded a fair comparison between the new method and the classical strain gage method. It is expected that future, more refined control over the applied deformations will improve the resolution capability to the nanometer scale.

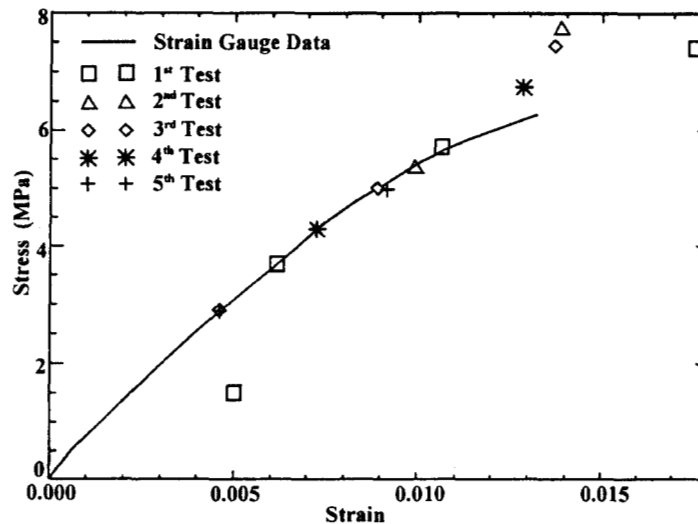


Fig. 7: Comparison of stress-strain response for unplasticized polyvinyl-chloride; symbols denote results from STM/DIC (300 nm gage) and the full curve represents data from a foil strain gage.

There is, at present, no tool and method available or on the horizon that has the potential of what is proposed here for making strain measurements at a comparable size scale. Once perfected, this method will allow micro-engineering to proceed to uncharted territories with applications in materials engineering, Aerospace and terrestrial transportation, in medicine and in communications; virtually all human endeavors at the forefront of technology may be affected.

C. An Example of a Study Germane to Reliability Analysis

Inasmuch as the purpose of the JPL/Campus interaction is to provide experimental tools for quantitative strength evaluations, generic test geometries rather than specific device geometries are preferred. If these are not available through the MEMS Exchange program, they will have to be manufactured at JPL. Although specimens of the type "A" shown in figure 8A can be produced at JPL, a question exists regarding the narrowness of the "crack" shown in figure 8B.

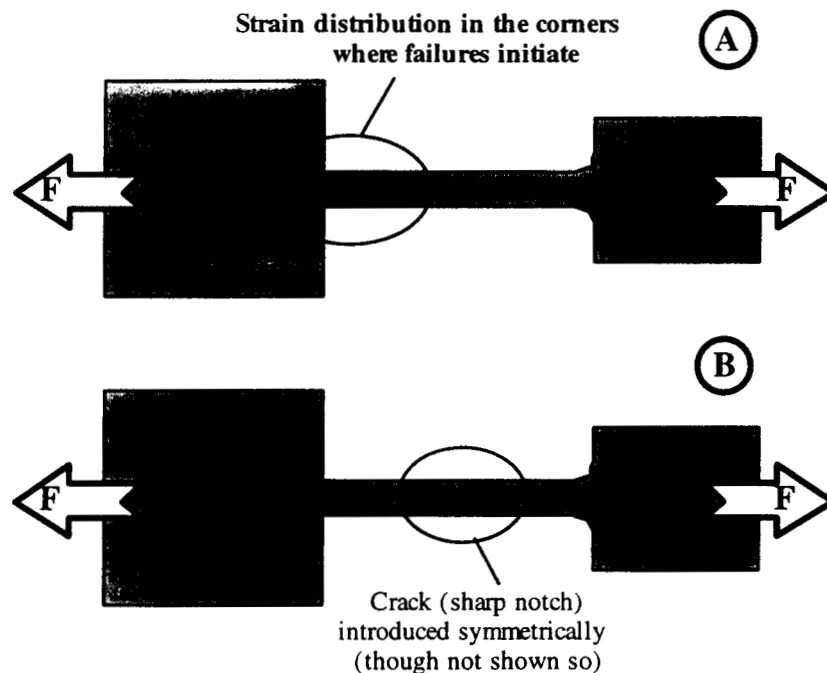


Figure 8: Generic (preliminary) test geometries to determine stress concentrations around typical defects;
A: Stress/strain field near corner;
B: Stress/strain field at tip of sharp notch (crack).

To achieve a one- or two-micron wide opening may require manufacture at MCNC or another affiliation of JPL's.

While this question is being resolved, the campus group will finalize the design of the gripping and straining device (a nano-test frame) to provide sufficient pulling force for fracturing specimens. This capability will require fixation of specimen ends by other than friction means (present configuration for stress-strain data), preferably by radiation-induced bonding.

Specific results pursued are the determination of the strain distribution in the vicinity of the specimen corners [figure 8A] and at the tip of the crack [figure 8B]. These results are to be compared to numerically analytical results based on finite element computations employing established bulk properties for assessing agreement or divergence. Complete agreement (within experimental error bounds) would indicate that bulk properties are appropriate and that macroscopic analysis methods are directly transferable from the macro- to the micron and nano-scales. Any observed differences would establish the degree by which microscopic geometries need to incorporate nano-scale properties into a fracture analysis. We expect that a complete experimental/analytical fracture analysis with the appropriate mechanical properties will be achieved. As part of the experiments, the DIC method will be refined by accounting for or subtracting errors inherent in the scanning microscope operation.

